FATIGUE LIFE AND MECHANICAL BEHAVIOUR OF ALUMINIUM ALLOY AA6061 CHIPS PREPARED BY HOT EXTRUSION PROCESS

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DEDICATION

To my mother and father.
To my wife Hanan, my daughters Kawthar and Zahraa and my sons Haider and Ali.
Very special thanks to my beloved family for their support, encouragement and prayer to Allah for gaining the successful completion of my study.

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In the name of Allah, the Beneficent, the Merciful

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ABSTRACT

The global engineering activities nowadays are focusing on green and eco-friendly innovations. This has made the recycled materials a lucrative research sector. A study on fatigue life and mechanical behaviour of aluminium alloy aa6061 chips prepared by hot extrusion process was undertaken in this research. The fatigue, mechanical and physical properties of extruded products were investigated under varying preheating temperatures (PHT) of 450 °C, 500 °C, 550 °C and preheating times (PHTi) of 1 hr, 2 hrs, and 3 hrs respectively. From the Design of Experiments (DOE) principle, 11 samples (S1-S11) selected were sufficient to investigate the initial mechanical properties in which the optimum sample was later identified. This optimum sample was then heat treated to investigate the effect of heat treatment on the fatigue life. Comparisons were made with non-heat treated optimum sample and sample from the as-received material. The highest Ultimate Tensile Strength (UTS) was 174.62 MPa obtained at maximum PHT of 550 °C in sample 8. ANOVA indicate that PHT and PHTi parameters are significant over the UTS. For the microhardness, sample 5 is a profile extruded at 450 °C PHT and 1 hr PHTi demonstrated the maximum obtainable Vickers hardness of 55.69 HV. On top of that, the ANOVA showed that PHT contributes significantly to the microhardness while the PHTi parameter is not. In addition, the peak UTS of 340 MPa was observed in the heat treated extrudates, improved about 95 % compared to optimum UTS of 174.62 MPa in non-heat treated sample. While, the sample tested in as-received aluminium only resulted in 298 MPa. In fatigue analysis, the fatigue life endurance for three different cases was indicated by the S-N curve. The research successful demonstrated that the fatigue life endurance and mechanical properties of directly recycled aluminium alloy AA6061 chips can be improved about 28 % through the heat treatment. The preheating temperature was the key parameters that control the overall mechanical properties in direct recycling of aluminium alloy AA606 chips.

ABSTRAK

Aktiviti kejuruteraan global masa kini memfokuskan kepada inovasi hijau dan mesra alam. Ini telah menyebabkan bahan-bahan kitar semula menjadi satu sektor penyelidikan yang menguntungkan. Satu kajian mengenai jangkahayat kelesuan dan sifat-sifat mekanikal bagi tatal aloi aluminium AA6061 yang dihasilkan melalui kaedah kitar semula dalam keadaan pepejal melalui proses penyemperitan panas telah dilaksanakan. Sifat-sifat kelesuan, mekanikal dan fizikal produk yang disemperit dikaji di bawah suhu pemanasan yang berbeza-beza (PHT) iaitu pada 450 ° C, 500 ° C, 550 ° C dan masa prapemanasan (PHTi) selama 1 jam, 2 jam, dan 3 jam. Reka Bentuk Eksperimen (DOE) mencadangkan pemilihan 11 sampel (S1-S11) bagi kajian awal sifat-sifat mekanikal dimana sampel optimum akan dikenalpasti kemudiannya. Sampel optimum kemudiannya akan dirawat haba untuk mengkaji kesannya terhadap jangkahayat kelesuan bahan. Perbandingan dilakukan dengan sampel optimum yang tidak dirawat haba dan sampel bahan asal. Kekuatan tegangan tertinggi (UTS) diperolehi adalah 174.62 MPa pada suhu 550 °C (sampel 8). Analisa Variasi (ANOVA) menunjukkan parameter PHT dan PHTi sangat mempengaruhi UTS. Bagi kekerasan mikro, sampel 5 yang disemperit pada suhu 450 °C dan dipanaskan selama 1 jam menghasilkan kekerasan Vickers maksimum 55.6886 HV. Di samping itu, ANOVA menunjukkan faktor PHT sangat mempengaruhi kekerasan bahan sementara parameter PHTi tidak. Selain itu, maksimum UTS 340 MPa didapati pada sampel dirawat haba, ianya meningkat lebih kurang 95% berbanding dengan sampel yang tidak dirawat haba. Dalam pada itu, sampel yang diuji daripada aluminium asal hanya menghasilkan UTS 298 MPa. Jangkahayat kelesuan bagi tiga kes berbeza yang dikaji ini ditunjukkan oleh lengkung S-N. Kajian ini berjaya menunjukkan ketahanan jangkahayat kelesuan dan sifat mekanik aloi aluminium yang dikitar semula secara terus boleh diperbaiki 28% melalui proses rawatan haba. Suhu prapemanasan adalah parameter utama didapati mengawal keseluruhan sifat-sifat mekanikal tatal aluminium AA6061 yang dikitar semula secara langsung.

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LIST OF SYMBOLS AND ABBREVIATION

°C	Degree Centigrade
ANOVA	Analysis of Variance
DOE	Design of Experimental
ER	Extrusion Ratio
LOM	Light Optical Microscope
N	Number of Cycles
P Value	Test of Comparing Model Variance
PHT	Preheating Temperature
PHTi	Preheating Time
RT	Room Temperature
S	Stress
SEM	Scanning Electron Microscope
Tm	Melting Point
UTHM	Universiti Tun Hussein onn Malaysia
UTS	Ultimate Tensile Strength
XRD	X-ray Diffraction
YS	Yield strength
σ_r	Stress amplitude

CHAPTER 1

INTRODUCTION

1.1 Overview

Nowadays, an economical process has been discovered instead of conventional recycling, and this process involves the direct treatment of the chip of the metal. These has thrown open a 'box of challenges' for the design and materials engineer. The challenges of converting wastes to wealth is where innovations lie, on the one hand. However, the good news is that recycling, especially in the aluminium industry is a continuous and sustainable practice (Khamis *et al.*, 2015; Nwachukwu *et al.*, 2017). This is not because aluminium constitutes 8% of the earth crust (Nwachukwu *et al.*, 2017), but because it has some amazing properties of strength-to-weight ratio and most importantly; alloy ability. In fact, rear earth metals are now added in addition to the long list of composites that could be formed with aluminium and its alloys.

In addition to the huge energy demand in the aluminium production process, the quest for fuel consumption in the transportation industry, oil spills as a result of demand also creates environmental pollution and calls for weight reduction. Here, aluminium chips and direct extrusion is in the forefront in the aluminium recycling industry for maximum recovery and energy savings (Mahinroosta & Allahverdi, 2018; Msebawi *et al.*, 2019).

The CO_2 emissions reduction is attaining more and more importance globally to avoid global warming produced due to the production of green-house gases. Because of that, there is severe necessity to reduce energy consumption in transportation and each field of industrial practices, electrical and electronic, household and window frame in building applications is the foremost element in current industrial growth. In manufacturing industries; the energy consumption analyses have revealed that maximum amount of the energy is consummated in the production of material: aluminium or steel and not for additional manufacturing stages such as cutting or forming (Tekkaya *et al.,* 2009).

Metal chip are formed through machining of ductile materials. For instance, in lathe machine operations, industrial production that involves turning and boring of metals (aluminium chips form coils and are easily collected in contract to brittle metals whose powder chips collection may require sophisticated technology). These wastes are resources that are further processed through a well-managed collection, treatment and cleaning processes. The size of the chips are reduced by using metal crushers, dryers for removing moisture contents, impurity separators, and an integrated conveyor system designed to manage the chips production and operations process (Das, 2006).

The justification for drying operations is hinged on the wet nature of the chips as a result of cooling during machining and oil stains picked up from the tools and machine generally. This is to support the re-melted process for efficient and economical recycling process (Haraldsson & Johansson, 2018; Mahinroosta & Allahverdi, 2018).

In the field of forming and cutting technology, usually, sufficient quantity of energy is not consumed during manufacturing process, rather for the production of primary input materials. Part of that is exhausted in formation of ingots after mining. However; secondary material, made from melting after recycling attracts the remaining part of the energy. Güley *et al* (2011) observed that this might consume about 20 GJ/ton (function of scrap condition).

These aforementioned reasons and the need for reduction of energy consumption, CO_2 emissions reduction and carbon footprint during manufacturing methods had raised bar and called for an innovative process on the recycling chain. A combination of optimized primary material usage and a reduction in processing steps is highly required.

Recycling of aluminium alloy scraps and chip are often done through conventional re-melting (Bertram *et al.,* 2009; Capuzzi & Timelli, 2018; Yang *et al.,* 2005) where part of the alloy is recovered and others are lost to the production process in addition to the energy demand. However, Mustapa *et al.,* (2015) joined their opinions with that of Das (2006) to submit that the high costs of labour and energy associated with the melting recycling of the chips and scraps are linked to the oxidation, hence the call for more efficient recovery method.

The cost related with the protection of environment is further increased the overall costs. Currently, numerous advanced methods have been recommended to recycle aluminium chips by employing direct hot extrusion (Gronostajski *et al.*, (2000); Haase & Tekkaya, (2014); Shahrom & Yusoff, (2017) for options in direct extrusion processes. The chief advantage is the energy consumption where it can be seen that energy used for the direct recycling method is less than the required energy in conventional recycling method as shown in Figure 1.1.

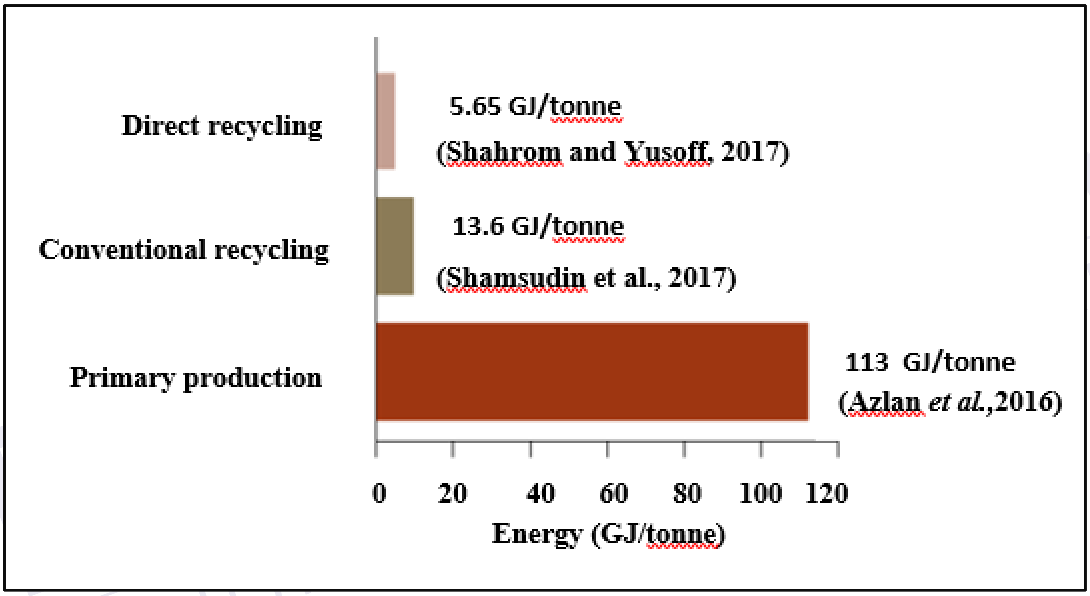

Figure 1.1: Energy consumption for the direct, conventional recycling and primary production

From Figure 1.1, the primary production process is a production process that involves the conversion of bauxite to aluminium alloy. The conventional recycling process involves melting of aluminium alloy scraps to recover the aluminium while the direct recycling process eliminates the melting stage in the process of recovery of aluminium alloys. While selling the direct extrusion option, Msebawi *et al.*, (2019) outlined the basic stages to include preparing of billets by cold compaction of the chips with various pre heating temperature and time which are then hot-extruded. Earlier, Tekkaya *et al.*, (2009) reported on the potentials inherent in the adoption of hot extrusion of chips based on Al 6060 and the possibilities of mixing Al 6060 chips with SiC particles. Their report may have footings from the experience reported by Gronostajski *et al.*, (1997) where chips of Al alloys was mixed with tungsten powder of 80 mesh and directly converted into the final product by hot extrusion process. A follow up of this has been done by several authors. Notable among these efforts are the works of (Güley *et al.,* 2011; Haase *et al.,* 2012; Misiolek *et al.,* 2012).

This research work planned a new technique of direct recycling of aluminium chips, in which scraps and chips are recycled by employing plastic deformation processes: hot or cold pressing followed by hot extrusion as was opined by (Gronostajski *et al.*, 2000). This method has shown improved strength due to grain refinement and homogeneous dispersion of oxide precipitates in the metal matrix.

The recycling of aluminium and its alloys by direct recycling method is comparatively easy, requires less energy with minimal environmental effect in support of the eco-innovation practices (Sanni, 2018). Therefore, the purpose to reduce the consumption of energy in industries (industries in Iraq suffers and the rest of the world are in quest for less energy consumption) process (Kazem & Chaichan (2012) and the necessity to decrease CO_2 emission in efforts to reduce global warming. Sequel to that, it is prime important to study the direct recycling of Aluminium chips as a secondary resource. For us, this method is an innovation worthy of exploring in support of the efforts of the government in Green Technology research and developmental goal.

1.2 Background of study

The Stern patent of 1945, Stern & Gardens (1945) was an open invitation for researchers to further investigate the possibilities of recycling aluminium alloy scraps. The invention was first of its kind that showcased the treatment of aluminium wastes and scraps using the direct recycling method. Their discovery was followed by the inventions of William and John (1957) where the potentials in treatment of aluminium alloy scraps using the solid sates method was further explored. These two major findings informed the choices demonstrated in the studies of (Shamsudin *et al.,* 2016). In their review, the multiple solid-state methods of converting aluminium through plastic deformation (PD) and powder metallurgy (PM) supported the findings of (Gronostajski *et al.*,1997).

Gronostajski *et al.,* (1997) used the design proposed by Stern to study the physical and mechanical properties of direct recycled aluminium, produced using extrusion method. This earlier study cantered on proposing an improved density and strength of products obtained by PM technique, without melting processes into a finished product. The high temperature used in the study supported formation of nearly mushy zones which assisted the plastic flow matrix into voids and pores of the aluminium matrix. Further mentioned were the relatively low extrusion rate, lubricants and other extrusion inhibiting parameters Haase *et al.,* (2012) stimulated the diffusional transportation of matter.

Arguably, convinced by the good surface finish, quality and density of the product of direct recycling of aluminium chips obtained from their previous studies, Gronostajski *et al.,* (2000) innovated and proposed a novel technique of recycling aluminium and aluminium alloy chip. Here, further steps that were missing in the previous studies were incorporated. The method covered preparation of aluminium chips for the recyclable alloys, the cleaning of the chips from impurities, segregation of the chips and the combination of the chips to crushed items. This technique was successfully implemented in the production of composite materials and yielded enviable mechanical properties at room and elevated temperature.

Three years after the successes recorded by the Gronostajski *et al.,* (2000) research team, Fogagnolo *et al.,* (2003) considered a combination of cold and hot pressing methods. The experimental studies focused on recycling aluminium alloy chips and aluminium matrix composite chips. The justification for the result obtained in their research was hinged on the refinement of microstructure and the dispersion of the aluminium oxide within the matrix during the extrusion process.

However, the pours and voids were not fully occupied by aluminium chips after the extrusion. The microstructure analysis revealed that these voids were crack sites that eventually lead to the reduction in mechanical properties of the formed composite in contrast to the recycled material. Moreover, the roles of voids in mechanical properties are detrimental and beneficial to mechanical properties. When voids are detrimental to mechanical properties, they block stress field of a migrating dislocations. The blockage of the stress field leads to reduction in mechanical properties.

Scholars have conducted spectrum of experiments on the fatigue properties of recycled aluminium alloy chips for over two decades. Arguably, some results full supported the increase in mechanical and fatigue related properties Haase *et al.,* (2012) while others reported Chiba *et al.,* (2011); Chino *et al.,* (2006) contrary opinions. The reason for the poor fatigue behaviour was due to the crack formations resulting from the oxides and contaminants in the recycled alloy. In the same vein, while some result are controversial, others had presented better cases (even supporting their cases with innovative extrusion method) (Selmy *et al.,* 2016). Upsurge in fatigue strength/lifetime, and/or ultimate tensile and yield strength were linked to the microstructure and surface integrity of the extruded aluminium alloy when pores minimal (Haase & Tekkaya, 2014).

Chino *et al.*,(2006) studied fatigue behavior of AZ31 magnesium alloy formed by solid-state recycling through hot extrusion route. The key findings in their study were that the reduction in fatigue life of the recycled alloy was linked to the crack formed due to oxide contamination. The pours were so significant to the extent that it was detrimental to the fatigue resistance of the alloy, albeit the reduction in grain size from 15.2 µm in the as received alloy to 13.3 µm for the recycled alloy.

Maoling *et al.,* (2008) worked on effect of chip size on mechanical property and microstructure of AZ91D magnesium alloy prepared by solid state recycling. The discovered a higher elongation to failure and an improved ultimate tensile strength. This improvement was attributed to the ambient oxide in the recycled specimen. While, excessive oxide in the recycled specimen might be detrimental to the elongation to failure.

Recently, Tekkaya *et al.,* (2009) experimented on the AA6060 aluminium chips using direct hot extrusion method and different geometries. They collected aluminium scraps from milling machine to form chips. The results shown that using billets manufacturing through AA6060 chips can provide same microstructural mechanical and properties as by utilizing conventional cast aluminium billets.

In an experiment performed by Lee *et al.,* (2010) to investigate the effect of UNSM (Ultrasonic Nano-Crystal Surface Modification) on fatigue strength in AA6061-T6 aluminium alloy, it was discovered that samples with coated surfaces had better surface hardness engineered by reduction in surface roughness. The study by Tillová *et al.,* (2017) had suggested the need for some surface treatment to minimize the effect of machining on fatigue. It was the treatment done by Lee and his team that increased the fatigue strength with about 50%.

The above report experimented 7 samples with various surface modifications. In all, the UNSM technology delivered the optimum fatigue life in comparative with untreated specimens. The 40% surface hardness (surface roughness decreased 3.4 ~ 8.7 times) recorded was responsible for the long fatigue crack initiation and lives.

This study argued that the cost implications of modifying the surface with this technology may not pay-off, except otherwise relevant, especially in recycling of aluminium alloys.

Before the Khamis *et al.,* (2015) adoption of Response surface methodology (RSM) for optimization of measured parameters, most of the experiments were conducted through the conventional method. However, it may be challenging to quantitatively describe the relationship between obtained responses in the face of array of variables. Their interest centred on chip size, pre-compaction, and holding time. It was justified in this research that the Central composite design (CCD) based on face centred cubic design was suitable to measure desired parameter.

The report revealed that (of the three parameters considered) holding time, pre-compaction, and chip size were influential, in that order on the mechanical properties of the recycled aluminium alloy. Inferentially, holding time affected the response the more as chip size affects the least. Hence they employed the hot pressing method on AA6061 aluminium alloy, if they had increased the holding time from 120 minutes to say 150 minutes better UTS could be obtained. Further mentioned was that 4 times pre-compaction cycle in combination with large chip size delivered the best UTS. Their result demonstrated that larger chip size may support higher holding temperature and devoid the hot pressed sample of excess pores. However, Mahdi *et al.,* (2015) argued that after 20 minutes of holding time, mechanical properties may decrease due to cracks spurred by excessive heat.

From the foregoing, following the works of Chen and Thomson (2004), Haase *et al.*, (2012), Rady *et al.*, (2019a) and Toulfatzis *et al.*, (2018) it is clearer that eight major parameters could influence the mechanical and fatigue properties of extruded products as presented in Figure 1.2.

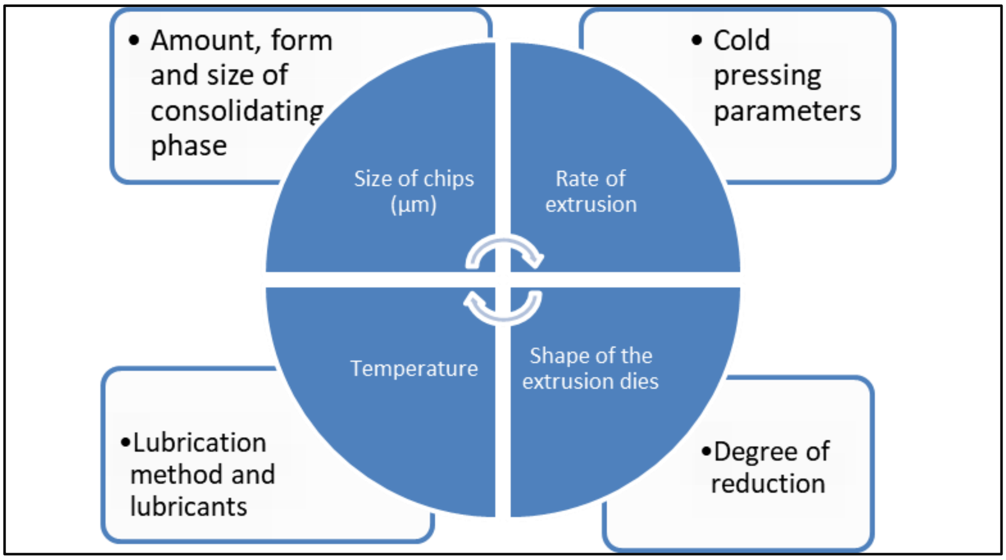

Figure 1.2: Parameters influencing mechanical and fatigue properties of extruded products

1.3 Problem statement

The global and future engineering activities are focusing more on green and eco-innovations. The transportation industry nowadays was also demanded to reduce the emissions drastically. The awareness among consumers on the global warming impact has led to more attention is given on low energy metal production.

Aluminium and its alloys are useful as parent/matrix in industries, but, a huge amount of wastes is produced as by-product through the process. The wastes are either in the form of chips during turning/milling or in other forms such as pins, drosses, runners and etc. that will end up in the recycle bin. However, these wastes can be fed back to smelters and recycled by melting. Nevertheless, conventional recycling of aluminium by remelting led to low recovery of material due to losses from oxidation, dross and many other associated parts. The complexity in conventional recycling ranges from large number of operations, high operating costs, and high energy consumption.

Environmentalists may not have issues with the reuse of recycled aluminium, but with the greenhouse gas emission released during the remelting, this led to a major worry among them. To economists, operation manager, engineer and all other professionals, they queried a lot on the materials lost and the use of an excessive energy during remelting (Boin & Bertram, (2005); Msebawi et al., (2019)). Other than labour

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